Interannual Variations of River Water Storage in the Rio Negro River basin from a Multiple Satellite Approach

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INTRODUCTION

Spatio-temporal variations of water volume over inundated areas located in large river basin have been determined using combined observations from a multi-satellite inundation dataset, the Topex/Poseidon (T/P) altimetry satellite, and in-situ hydrographic stations for the water levels over rivers and floodplains. We computed maps of monthly surface water volume change over eight successive years (1993-2000), the period of common availability of T/P and the multisatellite data. The basin of the Negro River (which area is around 700,000 km^2), the tributary which carries the largest discharge volume to the Amazon River, was selected as a test site. A strong seasonal signal is observed with minima in October and maxima in June. A strong interannual component is also present, particularly important during ENSO years. The results are consistent with previous water volume change obtained for two months over the same area using the JERS mosaic data. The surface water volume change is then compared to the total (i.e., surface plus underground) water volume change inferred from the GRACE satellite for an average annual cycle. The water volume changes are also evaluated using in-situ discharge measurements and the rain GPCP product. It clearly shows high potentials for the new technique to bring valuable information to improve our understanding of large river basin hydrologic processes and modeling and will be extended soon to other large watersheds.

THE STUDY REGION

The Negro River sub-basin (700,000 km^2, Fig. 1) occupies 12% of the Amazon basin. It is the largest tributary to the Amazon River and ranks as the fifth largest river in the world for its water discharge [1]. The Negro joins the Solimões River to form the Amazon River downstream from Manaus, and drains about 700,000 km² of Colombia (10%), Venezuela (6%), Guyana (2%) and Brazil (82%). It extends from 73.25° to 59.35° longitude West and from 5.4° North to 3.35° latitude South.

DATASETS

Multisatellite-Derived Inundation Dataset

The methodology developed to quantify the extent and seasonality of land inundation at the global scale with a suite of satellites is described in detail in [2] and [3]. A full description of each satellite observation and the potential of merged satellite data to study inundated surfaces can be found in [4].

Topex/Poseidon (T/P) Derived Water Levels

Along the satellite tracks shown in Fig. 1, we have considered 86 altimetry stations at which we have computed water level time-series from T/P altimetry data. These altimetry stations are identified in Fig. 1 by the white dots. The altimetry stations selected here are those which provide good quality water level time-series (according to data editing and error bars associated with each time-series — see below) and data gaps [5].

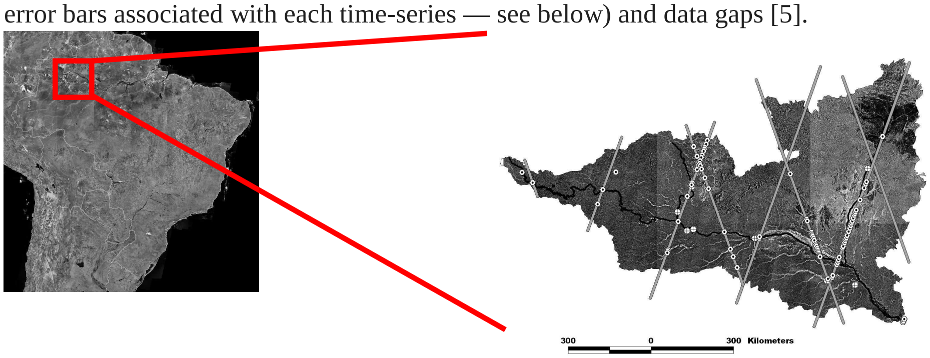

Fig. 1. Overview map of the Negro River basin in South America. The Negro River sub-basin from JERS-1 radar mosaic. Each thin white line accounts for a Topex/Poseidon track. Black dots in a white circle represent in-situ gauge stations, black dots in a white square, altimetric stations over the Negro River sub-basin.

In-Situ Water Level Time Series

We used daily measurements of water stage collected at 8 leveled gauging stations of the Brazilian Water Agency (Agencia Nacional de Aguas or ANA - http://www.ana.gov.br) in the Negro River basin (Fig. 1).

GRACE-Derived Land Water Solutions

The GRACE mission, launched in 2002 March, is devoted to measuring spatio-temporal changes in Earth's gravity field that results mainly from water mass redistribution among the surface fluid envelops. We use the land water and snow solutions derived from the inversion of 35 GRACE geoids from the third data release by GeoForschungZentrum (GFZ-RL03), as presented in [6], [7]. These solutions range from February 2003 to February 2006, with a few missing months (June 2003 and January 2004) and a spatial resolution of 400 km.

METHODS

Water Level Maps

Monthly maps of water level can be estimated over the Negro River basin. As the temporal resolution of the inundation map is one month, we create monthly averages of the water levels for each altimetry or in-situ station. For a given month during the flood season, water levels were linearly interpolated over the flooded zones of the Negro River basin. A pixel of 25 km x 25 km is considered inundated when its percentage of inundated area is greater than 0. Maps of interpolated surface water levels with 25 km resolution have been constructed for each month between January 1993 and December 2000. Water levels are expressed with respect to the geoid.
The monthly maps of water level were produced by bilinear interpolation scheme to estimate the water level for each grid point. This method is widely described in [5] and [8].

Surface Water Maps

The variation of water volume corresponds to the difference of surface water levels integrated over the inundated surface. These variations $\delta V(t_i , t_{i-1})$, between two consecutive months numbered i and $i - 1$, over the floodplain S, are the sum of the products of the difference of surface water levels δh_j $(i , i - 1)$, with $j = 1, 2, \ldots$ inside S, by the elementary surfaces $R_e{}^2$ and the percentage of inundation P_j:

$$\delta V(i,i-1) = R_e{}^2 \delta\lambda\delta\theta \sum_{j\in S} P_j \delta h_j(\theta,\lambda,i,i-1)\sin(\theta_j) \qquad (1)$$

where $\delta\lambda$ and $\delta\theta$ are the sampling grid steps along longitude λ and latitude θ (0.22°), respectively, and R_e the mean radius of the Earth (6378 km). The surface and total water volume variations are expressed in km^3/month.
The error of the method was estimated using:

$$d\delta V = \sum_{i=1}^{n} \left(dS_i \delta h_i + S_i d\delta h_i \right) \qquad (2)$$

where: $d\delta V$ is the error on the water volume variation (δV), S_i is the i^{th} elementary surface, δh_i is the i^{th} elementary water level variation between two consecutive months, dS_i is the error on the i^{th} elementary surface, $d\delta h_i$ is the error on the i^{th} elementary water level variation between two consecutive months.
The error sources include misclassifications, T/P altimetry measurements and the linear interpolation method. The maximum error on the volume variation can be estimated as:

$$\Delta(\delta V_{\max}) \leq \Delta S \max \delta h_{\max} + S_{\max} \Delta(\delta h_{\max}) \qquad (3)$$

where: $\Delta(\delta V_{max})$ is the maximum error on the water volume variation (δV), S_{max} is the maximum flooded surface, δh_{max} is the maximum water level variation between two consecutive months, ΔS_{max} is the maximum error for the flooded surface, and $\Delta(\delta h_{max})$ is the maximum error for the water level variation between two consecutive months.

RESULTS

Spatial Distributions of Inundated Areas

Fig. 2 shows the average fractional inundation in the Negro River basin for 1994.

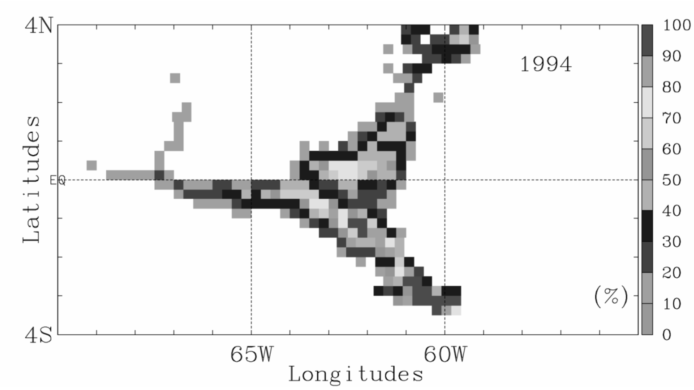

Fig. 2. Extent of inundation as estimated from the multi-satellite dataset for 1994 (% of inundated area per pixel).

The areas with a very high percentage of inundation (greater than 50%) are located on the lower part of the Negro River and the confluence between Negro and Branco rivers. The pixels corresponding to open waters, temporarily flooded pastures and low vegetation submerged by water during the flood in the Caracarai sub-basin (upper part of the Branco River) also exhibit a large percentage of inundation (between 20 and 70%). Inundation associated with Negro River basin is well captured, even in complex regions characterized by extensive flooding below dense vegetation canopies, with potentially high fractional inundation extent, low variability in the annual maximum, and quasi-permanent flooding (Fig. 2).
The seasonal and interannual variations of inundated areas in the Negro River basin are presented on Fig. 3. The maximum of inundated area is observed from May to July whereas the minimum is observed from November to February. Fig. 3 shows important interannual variability with maximum inundated area varying from 57,000 km2 (June 1996) to 42,000 km^2 (June 1997) and minimum inundated area varying from 28,000 km2 (January 1997) to 15,700 km^2 (December 1997), while 1998 is characterized by an important peak of inundated area (53,500 km^2) which occurs after a year of very low inundation. The low inundation in 1997 and high inundation in 1998 corresponds to the 1997/1998 El Niño Southern Oscillation (ENSO) event and its contrary (1998/1999 la Niña) which respectively cause decreases and increases of water levels and discharge in the Negro River basin and water storage in the whole Amazon basin.

Water Volume Variations

The monthly flood maps indicate that the flood period in the Negro River generally ranges from May to August, whereas low water period ranges from September to February. As an example for the 95-96 hydrological cycle, Fig. 4 shows maps of interpolated water levels for October 1995 and June 1996, which corresponds to the minimum and maximum respectively.

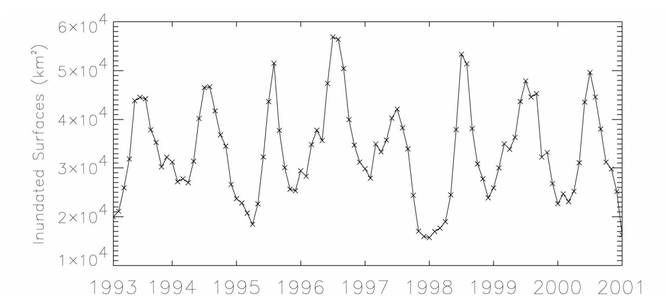

Fig. 3. Monthly inundated surfaces (km^2) in the Negro River basin between January 1993 to December 2000.

Fig. 5 presents the differences between two consecutive months of the mean water volume (i.e. the monthly change in floodplain water storage) averaged over the study area for 1993-2000. Positive variations are obtained between November and June. They are more important for the years 1996 and 1998. We also calculated the water storage changes during the 1995-1996 hydrological cycle of the Negro river. It corresponds to a volume variation of 167 km^3 for the whole floodplain.

Using (3), we have estimated the maximum error on the volume change in the lower Negro River basin with the following values:

S_{max} = 60,000 km² in year 2000 (cf. Fig. 3), δh_{max} = 5 m, ΔS_{max} = 10% of 60,000 km², $\Delta(\delta h_{max})$ = 0.5 m.

For the whole study zone, we obtained a maximum error of 39 km^3 over the period October 1995 – June 1996 for a total positive variation of 167 km^3, that is to say an error of 23%.

Fig. 6 compares the time series of the monthly changes in surface water volume and monthly variations of precipitation in the Negro River Basin for the period 1993 -2000. Both exhibit a similar behavior with a correlation of 0.61 for a time lag of one month (precipitation precedes surface storage variations), although precipitation variations are lower than surface water volume between January and March for years 1994, 1995 and 1998.

We then compared the mean annual cycle of monthly surface storage variations for 1993-2000 period with the mean annual cycle of monthly changes in total water storage from GRACE for 2003-2005 (Fig. 7). We notice that the average monthly GRACE-derived total water volume changes present almost in-phase fluctuations with the average monthly changes in surface water volume computed in the present study. The maxima and minima of the time-series are observed the same month, May and October respectively. The maximum surface water volume change represents between a third and a half of the total and the minimum roughly a half.

Due to the lack of a common period between the estimated surface water volume variations and GRACE observations, we compared the annual cycle of monthly-average surface storage variations for 1993-2000 with the annual cycle of changes in total storage from GRACE for 2003-2005.

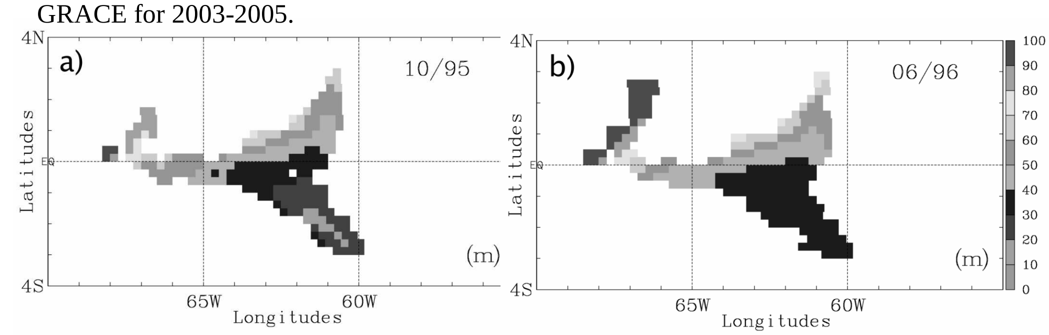

Fig. 4. Water level maps (with reference to GGM02C geoid) for October 1995 (a) and June 1996 (b).

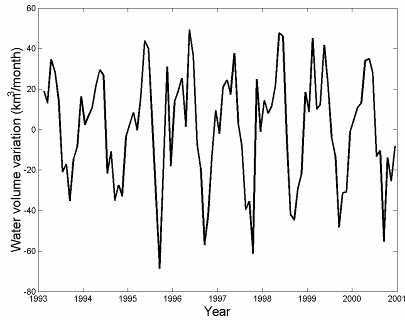

Fig. 5. Variation of surface water volume change from T/P radar altimetry and multi-satellite derived inundation dataset.

Figure 7 shows difference between these two, or the monthly changes in basin water storage outside of the river channel/floodplain system. The climatology hence defined showed that the total water storage of the Negro River basin is almost equally partitioned between surface water and the combination of soil moisture and groundwater.

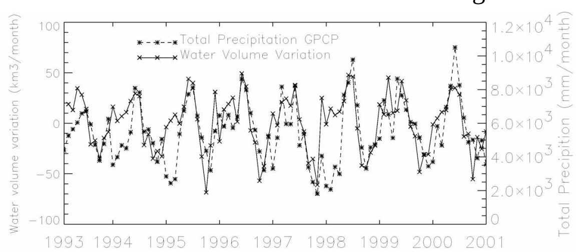

Fig. 6. Monthly variation of surface water volume change from T/P radar altimetry and multi-satellite derived inundation dataset and monthly precipitation rate over the Negro River basin from GPCP.

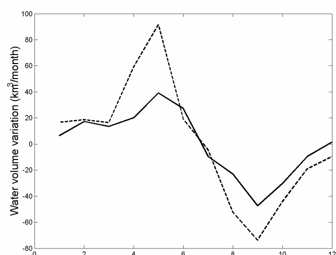

Fig. 7. Monthly variation of surface water volume change from T/P radar altimetry and multi-satellite derived inundation dataset averaged over 1993-2000 period (black line) and monthly variation of total land water volume change from GRACE averaged over 2003-2005 period (black dotted line).

CONCLUSION

Knowledge of surface water volumes has several potential applications, as flood monitoring and forecasting, sediment and nutrient transport assessment or floodplain geomorphology.
We also demonstrate the complementarity between several types of remote sensing data: multisatellite inundation dataset, water levels derived from radar altimetry and GRACE measurements of the total water storage. For the first time, a decomposition into several components of the total water storage from GRACE is presented.
These results will have implications for better monitoring the water cycle, and in particular improvements can be expected when additional data from current and future satellite missions are used.

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